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STUDY ON THE ARRIVAL MANAGER MAXIMIZING THE BENEFIT OF FOUR-DIMENSIONAL TRAJECTORY BASED OPERATIONS

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Abstract

This paper investigates an Extended Arrival Manager (E-AMAN) that maximizes the benefits of trajectory-based operations (TBO). To work alongside TBO, the E-AMAN algorithm is developed using the merging optimization method to simultaneously optimize trajectories, arrival sequence, and allocation of aircraft to parallel runways. Numerical simulations are performed under realistic simulation conditions based on the arrival traffic flow to Haneda Airport. The simulation results show that the E-AMAN algorithm can optimize the arrival traffic by minimizing the total fuel consumption and flight time of all aircraft. The trade-off between fuel consumption and flight time is also discussed in the simulation results.

1 Introduction

Arrival Manager (AMAN) is a ground-based air traffic controller support system aimed at smoothing arrival air traffic flow in the airspace near an airport. Arriving aircraft fly in various directions and merge trajectories near the airport. Air traffic controllers must establish arrival sequence for aircraft with sufficient separation. A major function of AMAN is to calculate and provide an appropriate arrival sequence and time of arrival for air traffic controllers.

In the conventional airspace-based operations, AMAN targets an area, the range of which is around 40–50 NM from the airport. However, along with the enhancement of trajectory-based operations (TBO), AMAN must also manage aircraft at a greater distance from the airport, e.g., from 150 to 200 NM. Such an AMAN is called the extended AMAN (E-AMAN) [1, 2].

According to the TBO concept proposed by the International Civil Aviation Organization (ICAO), aircraft fly along a four-dimensional (4D) trajectory defined by position and time. In the TBO concept, all trajectories are optimized to be conflict-free while minimizing the flight cost. TBO is expected to improve the efficiency and punctuality of future air transportation. One of the promising approaches for TBO is a model-based trajectory generation method. Base of Aircraft Data (BADA) developed by EUROCONTROL provides the capability of calculating an aircraft trajectory including aircraft dynamics and performance [3]. In addition, BADA provides models for various aircraft types distinguished by ICAO aircraft-type designators. BADA has been widely applied in trajectory prediction and trajectory optimization methods in generating 4D trajectories. To realize TBO, these methods have been implemented in the decision support tool for air traffic management [4, 5].

Regarding the AMAN algorithm, research studies are abundant on the sequencing optimization method, which optimizes the arrival sequence at the runway threshold. The conventional AMAN mainly focuses on the arrival sequence at the runway threshold; hence, the sequencing optimization method works well with an AMAN algorithm. However, the target range of E-AMAN is wider than that of the conventional AMAN. The E-AMAN algorithm is required to calculate not only the sequence but also the trajectory in collaboration with TBO. According to TBO, all aircraft fly along the optimal trajectories, but the benefits would decrease if the aircraft are bound to vectoring and holding near airports to establish the correct arrival sequence. From the flight cost point of view, adjusting the time of arrival at the airport at an earlier stage (for example, by changing cruise speed) is more efficient than doing so at close proximity to the airport (by holding near an airport) [6]. By including trajectory generation, E-AMAN can adjust the arrival trajectory at an earlier phase. Consequently, it can derive an optimal sequence without any detriment to the benefits of TBO. Furthermore, E-AMAN should also optimize the runway allocation of arriving aircraft to parallel runways. Most large-scale airports have such runways. E-AMAN can increase runway capacity by taking runway allocation into account.

This paper proposes a novel E-AMAN algorithm for collaboration with the TBO. E-AMAN has been developed based on a merging optimization method that can optimize the trajectory, sequence, and runway allocation simultaneously. Section 2 explains the difference between the sequencing and merging optimization methods. Section 3 shows the E-AMAN algorithm proposed herein. A merging optimization method is combined with the receding horizon strategy. Numerical simulations are conducted in Section 4 to demonstrate the capabilities of E-AMAN. Section 5 concludes this paper and describes future work related to this study.

2 Optimization Method for AMAN

2.1 Sequencing Optimization Method

Arriving aircraft have to land at an airport while maintaining sufficient separation to avoid wake turbulence generated by the leading aircraft. The wake turbulence separation depends on the type combination of the leading and following aircraft. The sequencing optimization method aims to increase runway capacity by swapping aircraft owing to the difference in separation. To indirectly increase the runway capacity, the total time of arrival is well set to the objective function to be minimized in the sequencing optimization method.

The arrival sequence is a discrete system; hence, the sequencing optimization problem is solved using a discrete-optimization methods, e.g., dynamic programming [7]. Beasley et al. used the mixed integer linear programming (MILP) to optimize the time of arrival, which is a linear continuous value, as well as the sequence [8]. Chen and Zhao formulated the sequencing optimization problem, including runway allocation, and optimized the sequence and runway allocation simultaneously [9]. Runway allocation is also a discrete system.

While the sequencing optimization method is suitable for optimizing the discrete system, it has difficulties in dealing with a continuous system. Thus, it cannot optimize the 4D trajectory, a nonlinear continuous system.

2.2 Merging Optimization Method

The optimization method capable of optimizing the trajectory and sequence simultaneously is called the merging optimization method. As mentioned in the previous section, the trajectory is a nonlinear continuous system and sequence and runway allocation are discrete systems. The merging trajectories include both nonlinear continuous and discrete systems; hence, the merging optimization problem is a hybrid system optimization problem, which is one of the most challenging problems to solve. The Traffic Management Advisor (TMA), one of the most successful AMAN algorithms, appears to be a merging optimization method [10]. However, TMA calculates the trajectory and sequence sequentially; therefore, TMA is a sequential control method rather than an optimization method. Though the TMA performs outstandingly even as an E-AMAN, this paper focuses on the optimization method-based E-AMAN algorithms.

Several research studies have attempted to solve this problem. Michelin et al. combined the optimal control based-trajectory optimization method and simulated annealing [11]. Ny and Pappas applied mixed integer geometric programming (MIGP), which is a hybrid system optimization method [12]. These methods can optimize trajectories and sequence simultaneously, but they approximate the trajectory as a simple model that does not consider aircraft dynamics or performance model. Ohkubo et al. applied nonlinear optimal control to the multiple trajectory optimization problem with merging [13]. The nonlinear optimal control is a nonlinear continuous optimization method; hence, it can calculate the trajectory as a 4D trajectory. However, in this method, the arrival sequence was specified without optimization because it is difficult for nonlinear optimal control to treat the discrete system.

One straight-forward way to solve the merging optimization problem is to use mixed integer nonlinear programming (MINLP) approach. Bittner et al. successfully solved the merging optimization problem using this technique [14]. This optimization method can optimize both the trajectory and the sequence while the trajectories are calculated as 4D trajectories based on BADA, but significant computational time is required for optimization owing to the complexity of the hybrid system optimization problem. Grüter et al. developed a bi-level approach combining nonlinear optimal control and a genetic algorithm [15]. The bi-level approach iterates the trajectory optimization using nonlinear optimal control and performs sequencing optimization of the merging trajectory using the genetic algorithm. Authors proposed a simultaneous optimization method for trajectory and sequence (SOM-TS) to solve the merging optimization problem [16]. The SOM-TS could solve the merging optimization problem by transforming it into a criterion function. Furthermore, the SOM-TS was improved to optimize runway allocation [17]. The improved SOM-TS is called the simultaneous optimization method for trajectory, sequence, and runway allocation (SOM-TSR). The SOM-TSR can optimize the trajectories as 4D trajectories.

3 E-AMAN Algorithm

3.1 Simultaneous Optimization Method for Trajectory, Sequence, and Runway Allocation

The E-AMAN algorithm was developed based on the SOM-TSR, the concept of which is shown in Fig. 1. The top figure shows the merging optimization problem with parallel runways. Aircraft arriving at the same merging point have to maintain sufficient separation, but those arriving at different merging points do not have to consider this aspect. To optimize the merging trajectory while maintaining sufficient separation, the SOM-TSR transforms the merging optimization problem into a criterion function, as shown in the middle figure of Fig. 1. This function relates the arrival time t_f to the value of the objective function for trajectory J, such as fuel consumption or flight time. The criterion functions depicted by the solid lines are criterion functions for aircraft arriving at merging point 1 (MP1), whereas the dotted lines are criterion functions for merging point 2 (MP2). After transformation, the criterion

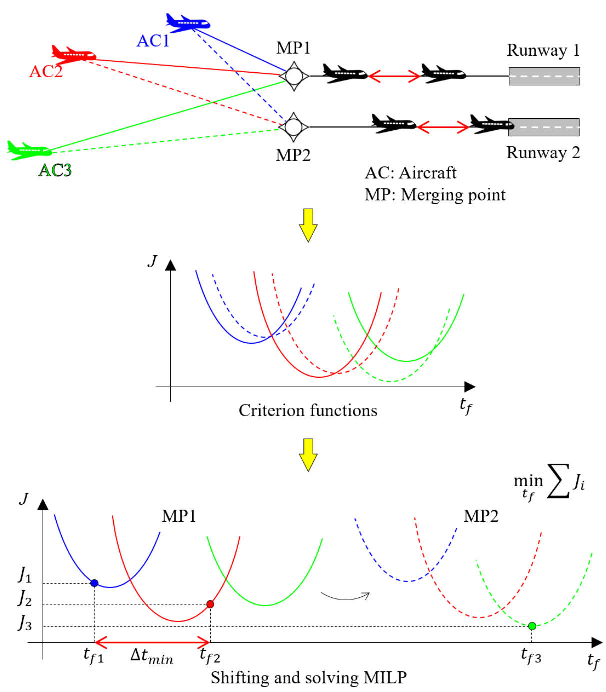

Fig. 1 Concept of the simultaneous optimization method for trajectory, sequence, and runway allocation (SOM-TSR).

functions for MP2 are shifted. According to the shifting process, the time separation constraints for aircraft arriving at the same merging point will be active, but those for aircraft arriving at different merging points will be inactive. Here, the original merging optimization problem can be expressed as an optimization problem in the criterion functions, minimizing the total J value, while all aircraft follow the criterion functions and maintain the minimum time separation Δt_{min}. SOM-TSR uses MILP to solve the optimization problem, as shown at the bottom of Fig. 1. The optimization problem can be formulated in the MILP form, as shown in Eqs. (1)–(3):

$$\min_{t_f} \sum_{i=1}^{N_{AC}} J_i, \tag{1}$$

$$\begin{aligned}
-a_{ijk}t_{fi} + J_i - Mc_{ijk} &\leq b_{ijk} \\
a_{ijk}t_{fi} - J_i - Mc_{ijk} &\leq -b_{ijk} \\
-t_{fi} - Mc_{ijk} &\leq -t_{fLijk} \\
t_{fi} - Mc_{ijk} &\leq t_{fUijk} \\
\sum_{k=1}^{2}\sum_{j=1}^{N_{div}} c_{ijk} &= 2N_{div} - 1 \\
&(i = 1,\dots,N_{AC}) \\
&(j = 1,\dots,N_{div}+1) \\
&(k = 1,2),
\end{aligned} \tag{2}$$

$$\begin{aligned}
t_{fp} - t_{fq} - Me_1 &\leq -\Delta t_{min} \\
-t_{fp} + t_{fq} - Me_2 &\leq -\Delta t_{min} \\
\sum_{k=1}^{2} e_k &= 1 \\
p, q = \{1,\dots,N_{AC} \mid p &< q\},
\end{aligned} \tag{3}$$

where the criterion functions are piecewise-linearized with N_{div} divisions to define into the MILP form. N_{AC} is the number of aircraft; a and b are the slope and intercept of the piecewise-linearized criterion function respectively; M is the Big-M for the Big-M method; and c and e are the binary variables. By solving the optimization problem using Eqs. (1)–(3), the optimal arrival times for all aircraft, including the optimal sequence and runway allocation, can be derived. The optimal merging trajectory can be derived by generating a trajectory with the optimal arrival time. Further details of the SOM-TSR are available in a previous study [17].

3.2 Receding Horizon Strategy

E-AMAN must optimize the arrival traffic successively entering its target area. However, it is not feasible to optimize all merging trajectories for 24 h due to the large amount of computational time. To optimize the merging trajectory of successive arrival aircraft, the receding horizon strategy is applied to E-AMAN. This strategy is well used for optimal feedback control. For the AMAN algorithm, Hu and Chen applied the receding horizon strategy to the sequencing optimization method [18].

Figure 2 shows the process for calculating the receding horizon for E-AMAN. The yellow area is the frozen window, the time length of is denoted as T_{FW}. The yellow and orange areas show the receding horizon, of the time length of which is denoted as T_{RH}. In the receding horizon strategy, only the aircraft in the receding horizon are subjected to optimization. At $t = 0$, E-AMAN optimizes only the merging trajectory of AC1 and AC2. After T_{FW} elapses, E-AMAN executes optimization again. Then, AC3 is also in the receding horizon; hence the optimization targets are AC1–AC3. At $t = 2T_{FW}$, AC1–AC3 are in the receding horizon. Additionally, AC1 is in the frozen window. E-AMAN optimizes the merging

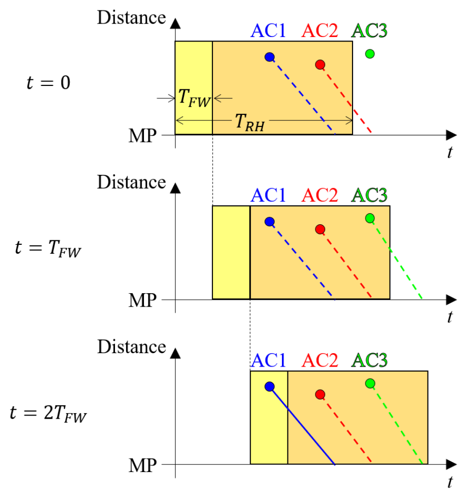

Fig. 2 Receding horizon strategy.

trajectories of AC1–AC3 and fixes the trajectory of AC1. Here, the dotted line shows the optimized trajectory and the solid line shows the fixed trajectory. E-AMAN optimizes the successive arrival aircraft by repeating this process as time proceeds.

4 Simulations

4.1 Simulation Conditions

To demonstrate the capability of E-AMAN, a simulated arrival traffic flow is generated for the simulation conditions. Figure 3 shows the typical traffic scenario arriving at the Haneda Airport (RJTT) during north wind operations, as derived from the radar data provided by the Japan Civil Aviation Bureau (JCAB). RJTT has four runways, with RWY34L and RWY34R being used for arrivals during north wind operations. The black dotted line shows the simulation area with a range of which is 200 NM from RJTT. Arriving aircraft mainly fly from the West and North directions with a ratio of approximately 3:1. Basically, aircraft coming from the West arrive at RWY34L and those coming from the North arrive at RWY34R in the current operational environment. To simulate the arrival traffic flow, arrival routes are designed as shown in Fig. 4. The designed routes are named based on the azimuth between RJTT and the entrance point: 260, 255, 250, 235, 230, 225, 010, 015, and 020. It is assumed that all aircraft fly along the routes without deviation. All routes connect to the approach routes via the existing waypoints ARLON, SINGO, and CREAM, as shown in Fig. 5 and Table 1. In the simulation, only the aircraft coming from the West are allowed to change their arrival runway; therefore, only the routes from the West have the approach routes to RWY34R.

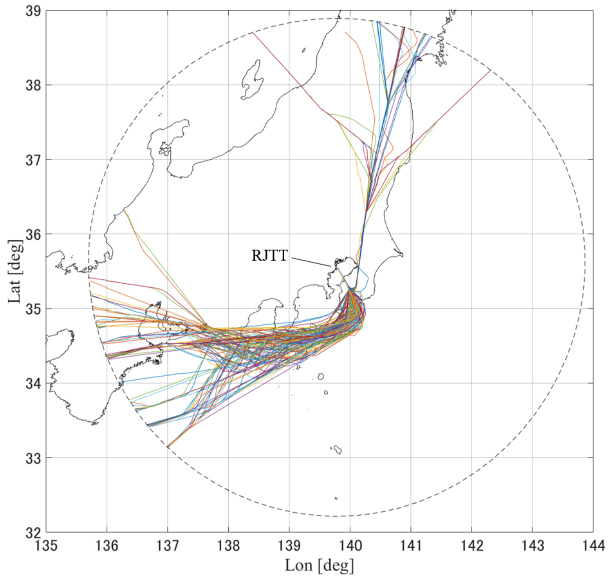

Fig. 3 Radar data for arrivals at RJTT.

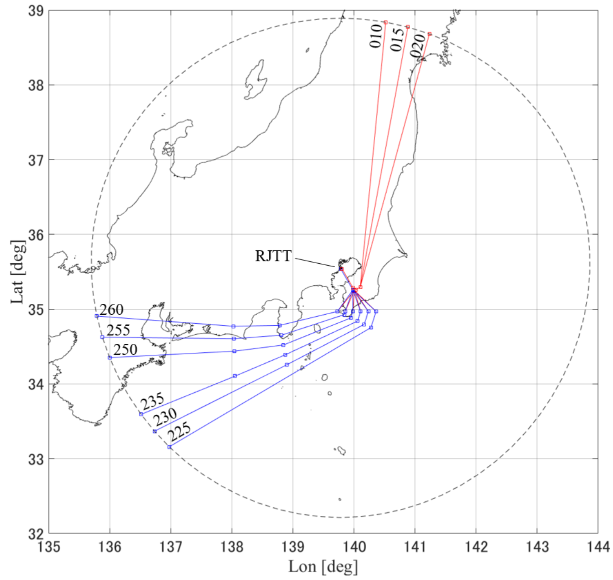

Fig. 4 Arrival routes for simulations.

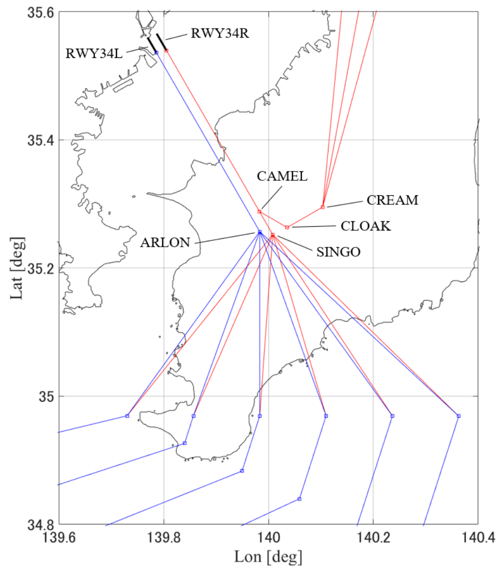

Fig. 5 Approach routes for simulations.

Table 1 Approach routes for simulations.

From West to RWY34L

Waypoint	Constraint
ARLON	At 5,000 ft
RWY34L	-

From West to RWY34R

Waypoint	Constraint
SINGO	At 4,000 ft
CAMEL	At 4,000 ft
RWY34R	-

From North to RWY34R

Waypoint	Constraint
CREAM	At 4,000 ft
CLOAK	At 4,000 ft
CAMEL	At 4,000 ft
RWY34R	-

The arrival traffic flow is set according to the conditions listed in Table 2. Arriving aircraft are defined randomly at a rate of 74 per hour from the West and North at a ratio of 3:1. The ratio of the aircraft types arriving at RJTT are extracted from the flight data management system (FDMS) of the JCAB for the period from January 01, 2017 to December 31, 2017. Aircraft types are generated according to the ratio derived from the FDMS data. The wind conditions are set as listed in Table 3 to simulate the actual wind conditions over the Japanese airspace. V_U and V_V denote the zonal and meridional winds respectively.

To minimize both fuel consumption $fuel$ and t_f, the objective function for the SOM-TSR, as shown in Eq. (1), is set as follows:

$$J = fuel + wt_f, \tag{4}$$

where w is a weighting factor between $fuel$ and t_f defining the cost index. Δt_{min} is set to 90 s at ARLON and CAMEL respectively. T_{FW} and T_{RH} are set as 60 and 600 s respectively. Accordingly, 13 aircraft are subject to merging optimization at the first iteration in this simulation. IBM®ILOG®CPLEX®12.7.1 is used to solve the optimization problem for criterion functions.

Table 2 Simulated arrival traffic flow.

ID	t_0 [s]	Route	Type	H_{PCRZ} [FL]
1	0	225	A	350
2	38	255	B	330
3	93	020	B	400
4	160	235	B	370
5	174	250	E	370
6	221	235	C	350
7	280	250	A	310
8	370	020	C	400
9	402	260	D	370
10	428	225	A	330
11	502	250	D	370
12	543	230	A	370
13	559	015	A	380
14	630	255	A	350
15	685	015	A	380
16	741	235	A	350
17	802	230	A	390
18	827	230	C	370
19	876	235	B	330
20	916	020	E	400
21	986	230	C	310
22	1042	225	C	350
23	1075	020	A	380
24	1131	235	A	310
25	1170	235	A	310
26	1243	015	A	380
27	1263	020	A	380
28	1326	235	A	370
29	1381	015	A	380
30	1382	230	A	370
31	1441	255	C	370
32	1490	250	B	370
33	1585	235	D	390
34	1635	230	E	370
35	1753	225	B	330
36	1786	230	B	330
37	1800	235	A	350

Table 3 Wind conditions.

Altitude [ft]	V_U [kt]	V_V [kt]
45,000	100	0
35,000	100	0
0	0	0

4.2 Trajectory Generation Method

SOM-TSR can use any trajectory generation method capable of providing t_f and J. The most optimal solution can be derived using the nonlinear optimal control-based trajectory optimization method, as discussed in previous researches [16, 17]. However, E-AMAN uses the integral calculation-based trajectory generation method to calculate realistic aircraft trajectories in this simulation.

The trajectory generation method calculates the trajectories based on BADA4 and the trajectory calculation logic of the flight management system (FMS), as discussed in a previous study [19]. Figure 6 shows simulation examples of the trajectory-generation method with different descent calibrated air speed (CAS). Hp is the pressure altitude; $Dist_{togo}$ is the distance to go; V_{CAS}, V_{TAS}, and V_{GS} are the CAS, true air speed (TAS), and ground speed (GS) respectively; Thr is the thrust; and FF is the fuel flow. The simulation conditions are set as AC18 in Table 2. In this simulation, the aircraft controls t_f by setting V_{CAS} in the descent phase; hence, each parameter has seven results with different V_{CAS} values. In all cases, the aircraft can descend while maintaining idle thrust. Additionally, the arrival time control using V_{CAS} is available for actual operations. Results show that E-AMAN could be a potential support tool to provide practical advisory information for the air traffic controllers by using the proposed trajectory generation method.

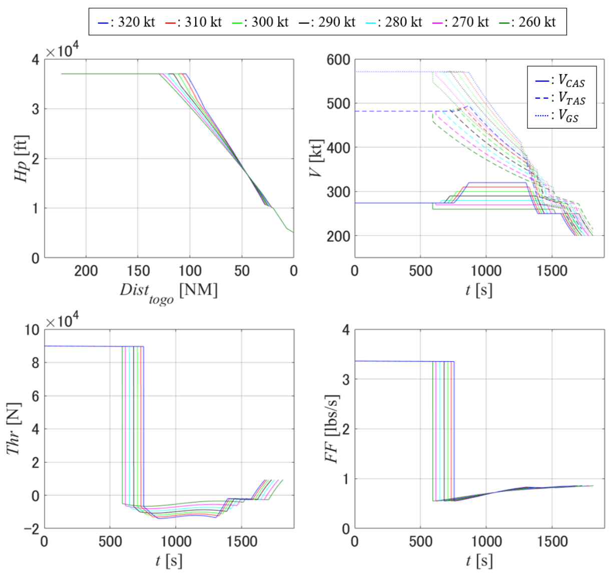

Fig. 6 Simulation example of the trajectory-generation method with different descent CAS.

The criterion function corresponding to this exemplary simulation is shown in Fig. 7. Each figure has a different w value, which ranges from 1 to 4. The figure shows that with large w, the criterion function prioritizes the reduction of t_f and vice versa. E-AMAN calculates the criterion functions for all aircraft, as summarized in Table 2, using the trajectory generation method. The merging trajectories, including runway allocation, are optimized by the SOM-TSR using the derived criterion functions.

4.3 Simulation Results

Figures 8 and 9 present the simulation results in the w = 1 and w = 4 cases, respectively. The figures show the entry time of the aircraft into the simulation area and the time of arrival at CAMEL (to RWY34R) and ARLON (to RWY34L). In the results, the t_f values and runway allocations for all aircraft are optimized while calculating the trajectories. All aircraft can maintain Δt_{min} = 90 s at the merging points. All trajectories are calculated using the trajectory generation method discussed in Section 4.2. Investigating the optimali-

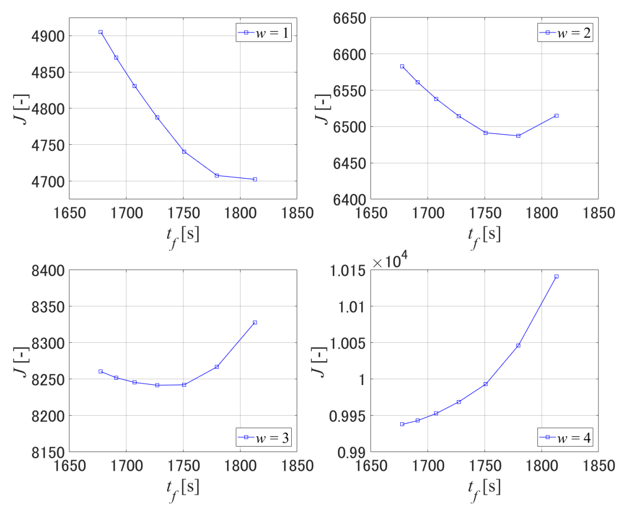

Fig. 7 Exemplary criterion function with different weighting factors.

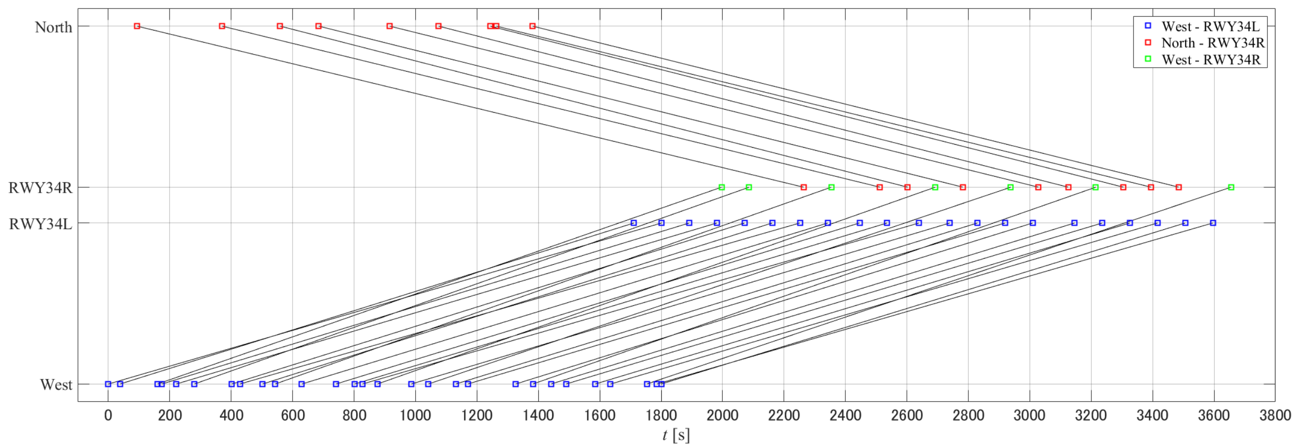

Fig. 8 Simulation results (case scenario $w = 1$).

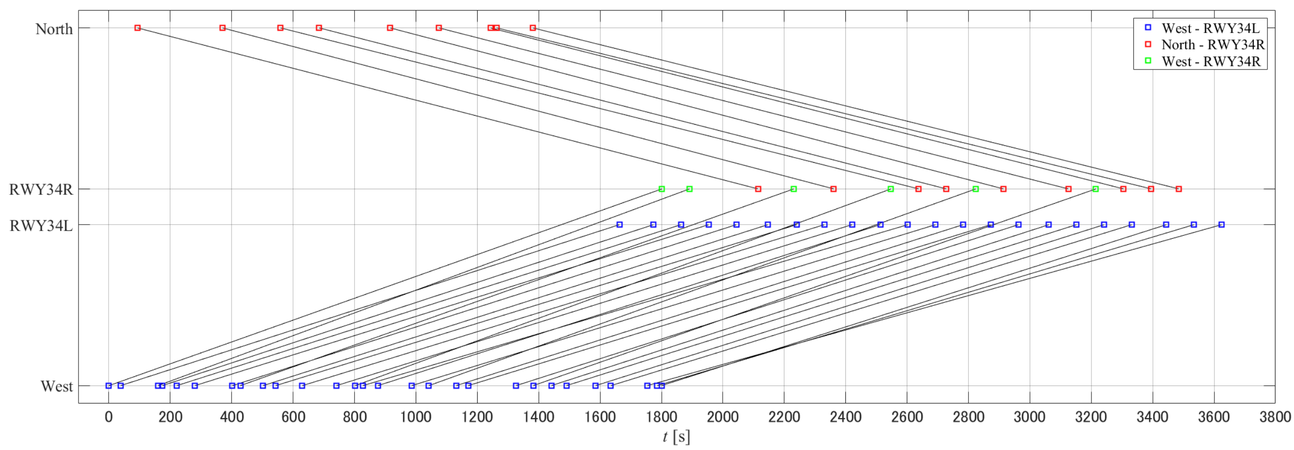

Fig. 9 Simulation results (case scenario $w = 4$).

ty of the optimization results derived from the SOM-TSR is beyond the scope of this paper, but it has been investigated in previous studies [17, 20].

The results show that in both cases, several aircraft flying from the West are allocated to RWY34R. For $w = 1$, there are seven such aircraft: AC4, AC7, AC12, AC19, AC22, AC30, and AC35. On the contrary, for $w = 4$, six such aircraft are allocated: AC1, AC4, AC10, AC17, AC22, and AC30.

With large w, E-AMAN prioritizes the reduction of t_f more than $fuel$. Results show that in case of $w = 4$, all the aircraft arrive earlier than they arrive in case of $w = 1$. To clarify the trade-off relationship between $fuel$ and t_f, Fig. 10 shows the total $fuel$ and t_f for all aircraft with different w values. The figure shows that along with increasing w, the total $fuel$ increases and the total t_f decreases. By adjusting w, E-AMAN can change the optimization target depending on the airspace and airport conditions. For example, under heavy traffic, E-AMAN can increase the throughput of the arriving aircraft by reducing the total t_f.

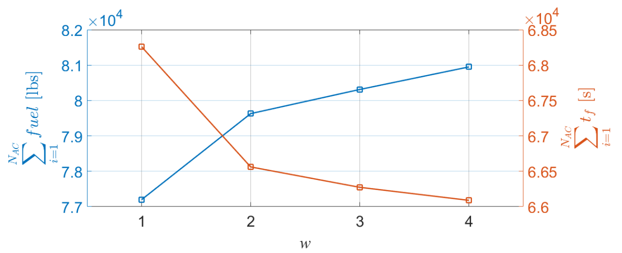

Fig. 10 Trade-off due to w.

4.4 Discussion

One of the optimization targets for E-AMAN is to increase the runway capacity. For this purpose, the objective function for the merging optimization method is set as shown in Eq. (4), which includes t_f to be minimized. By minimizing the total t_f value, they all arrive earlier; consequently, the runway capacity is indirectly increased. E-AMAN with a large w value can successfully minimize the total t_f more than with a small w, as shown in Fig. 10. However, Fig. 9 shows that E-AMAN allocates aircraft to parallel runways unevenly. Intuitively, to maximize the runway capacity, more aircraft should be allocated from the runway with heavy traffic to that with less traffic. On comparing Figs. 8 and 9, we found that the number of aircraft allocated in case of $w = 1$ is more than the case of $w = 4$, even though the results for $w = 4$ indicate that RWY34R must be allocated aircraft more than those in the $w = 1$ case to maximize the runway capacity. To resolve this inconsistency, the objective function for the SOM-TSR should be improved. The current objective function is reasonable because its form is similar to that of the cost index generally used to control aircraft. However, to attain the optimization target for E-AMAN, the objective function should be set to maximize the runway capacity directly. One potential solution is to minimizing the t_f value of the final arriving aircraft for both merging points instead of minimizing the total t_f value. With an appropriate objective function, E-AMAN will resolve the uneven usage of the parallel runways and maximize the runway capacity.

5 Conclusion

This paper proposes an E-AMAN algorithm, which can work in tandem with the TBO. Using the merging optimization method, E-AMAN can optimize the arrival sequence and runway allocation while calculating the arrival trajectories as 4D trajectories. This paper proposed the structure of E-AMAN algorithm as well as the simulation results to demonstrate its effectiveness. The results show that E-AMAN can minimize the total fuel consumption and flight times of all aircraft by manipulating the weighting factor between these quantities in the trade-off equation.

The future work for this study will improve the objective function for the merging optimization method. By replacing the minimization of the total flight time with the maximization of the runway capacity, E-AMAN will be able to derive more efficient results.

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7 License Agreement

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